Dynamics of medium-intensity dense water plumes in the Arkona Basin, Western Baltic Sea

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1 Introduction

The water exchange between the North Sea and the Baltic Sea is governed by baroclinic and barotropic processes which can be separated. Barotropically driven inflow into the Baltic Sea advects thick layers of saline Kattegat waters through the Danish straits towards the Arkona Sea. A barotropic inflow event transporting a sufficient amount of Kattegat waters into the Baltic Sea which finally arrives in the Gotland basin is called a **major inflow**. These events, occurring at the inter-annual time scale, are important for replacing the stagnant bottom water in the basins of the Baltic Sea. Inflow events transporting smaller amounts of Kattegat water into the Arkona Basin, the so-called **medium-intensity inflow** events, occur several times per year. Both ventilation processes, the major inflows and the medium-intensity inflow events, are important for maintaining the haline stratification and thus play a key role for the ecological regime of the entire Baltic Sea. Here we investigate the dynamics of such medium-intensity inflow events, since they may be subject to additional mixing due to the foundations of extensive off-shore wind farms which are projected in the area of the Arkona Sea. The inflow events over Darss Sill in the west of the Arkona Sea occur with a delay of about six days, such that the overflow of Drogden Sill can be investigated separately. Saline water spilling over the Drogden Sill propagates southward, flows around the Kriegers Flak and follows the depth contours along the southern Arkona Basin towards the Bornholmgatt (see figure 1). Such an inflow event has recently been observed in detail for the first time and some of the results are presented here.

Here, we are simulating medium-intensity inflow events over Drogden Sill with a highly idealised numerical model with stationary forcing, see section 2.1. Field observations of a mediumintensity inflow event are described in section 2.2. A detailed comparison between observations and model results is given in section 3. Finally some conclusions and a future outlook are presented in section 4.

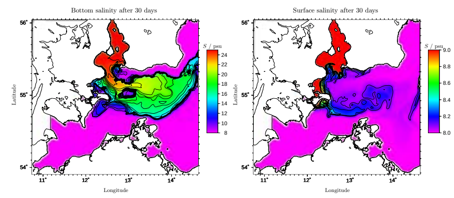

Figure 2: Near-bed (left panel) and near-surface (right panel) salt distribution after one month of simulation in a quasi-steady state. Note the different scales for the surface salinity plot, which emphasise the sinking of Sound water at the Drogden Sill and a small amount of mixing of saline waters into the surface brackish waters.

2 Methods

2.1 Numerical modelling

For simulating the dynamics of medium-intensity inflow events over Drogden Sill, the General Estuarine Transport Model (GETM, for details, see Burchard and Bolding [2002]) has been applied. The model was forced by a sea surface elevation slightly increased by 0.02 m at the boundary to the Kattegat in the North and a prescribed salinity for inflowing water of 25 psu, whilst the sea surface elevation was forced to zero elevation at the other open boundaries. As initial conditions, flow at rest with a salinity of 8 psu has been chosen. After about 30 days of simulation, a quasi-steady state is reached where the saline bottom water covers most of the Arkona Sea and is flowing over Bornholmgatt in the Bornholm Sea. A plot of the sea surface salinity shows that the saline water is detaching from the sea surface just south of Drogden Sill and only at a few positions, sea surface salinities above the background value of 8 psu is found. It is noteworthy that most of the saline water flowing through the Arkona Sea passes Kriegers Flak on its northern side. Kriegers Flak itself is not covered with saline bottom water.

This result is counter-intuitive in the sense that a mainly geostrophic propagation of the plume would result in flow along the isobaths and thus in this case a propagation southwards along the Danish coast and west of Kriegers Flak, with a turn to the east at Darss Sill and a further propagation along the southern boundary of the Arkona Sea towards Bornholmgatt. Thus the geostrophic balance of the near-bottom flow must be significantly modulated by bottom friction, which draws the plume down the slope. It is therefore useful and challenging to compare the model results to field observations of a medium-intensity inflow event over Drogden Sill, see the following section 2.2.

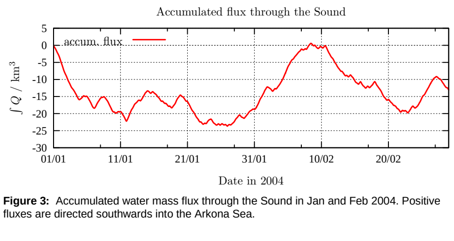

Figure 3: Accumulated water mass flux through the Sound in Jan and Feb 2004. Positive fluxes are directed southwards into the Arkona Sea.

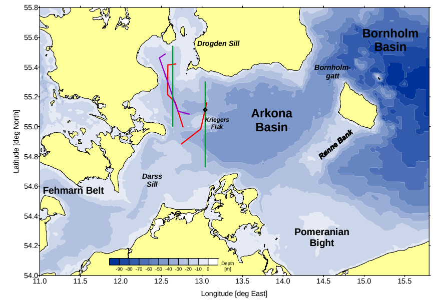

Figure 1: Bathymetric map of the Arkona Sea. The purple and red lines show the tracks for the observational sections (west: Feb 1./2, Drogden Sill section; east: Feb 5, Kriegers Flak section). The two green lines indicate the sections, as they have been extracted from the model simulation. The diamond indicates the position where the water column measurements have been carried out.

2.2 Field observations

From Jan 26 to Feb 13, 2004 the FWG Kiel (Germany) organised a field survey in the Arkona Sea during which a medium-intensity salt water inflow over Drogden Sill occurred, starting on Feb 1. This inflow event could be reconstructed on the basis of observed sealevel data. The accumulated volume flux over Drogden Sill (see figure 3) indicates that a significant inflow event must have started around Jan 31, lasting for about 10 days. During this time, CTD and ADCP sections have been carried out from Drogden Sill southwards and across Kriegers Flak, see figure 1. Furthermore, 24 hour station observations have been carried out at a position north of Kriegers Flak.

3 Results

The inflow event itself is documented by the CTD and ADCP section taken on Feb 1, see figure 4. Salinity values are up to 21 psu near Drogden Sill, which poses a significant gradient with respect to the ambient salinity of 8 psu. The along-plume (southward) velocity component reaches 0.5 ms^{-1} over a large portion of the plume. The plume thickness amounts to up to 10 m, with a well-defined halocline on top and a fairly well-mixed core of the plume. The high current velocity and the well-mixed core of the plume indicate high levels of turbulence within the plume. The observed propagation of the plume on Feb 1 is compared to results from the idealised simulation described in section 2.1 for day 8, see figure 5. Also the model results show high salinities of above 20 psu, with well-mixed conditions in the core of the plume and a strong halocline on top. The current velocity inside the plume is however significantly lower than in the observed plume, with southward velocities of up to 0.3 ms^{-1} only.

Another section is available for Feb 5 over Kriegers Flak, see figure 6. It can be clearly seen that the plume has reached the northern channel and forms a bottom layer of about 10 m thickness with salinities up to more than 18 psu. Although the noise to signal ratio for the ADCP measurements from the cruising ship was fairly high due to low concentration of particles in the water, an enhanced eastward current velocity of up to 0.5 ms^{-1} in the region of the halocline is observed.

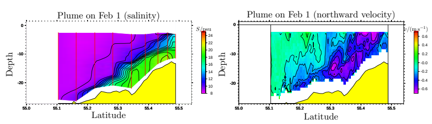

Figure 4: Observed salinity and northward velocity on a north-south transect south from Drogden Sill. (Feb 1, CTD and VMADCP measurements)

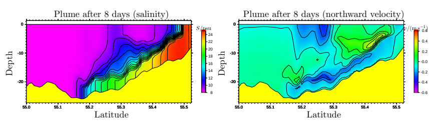

Figure 5: Simulated salinity and northward velocity after 8 days on a northsouth transect at 12°30'E south of Drogden Sill. (GETM model)

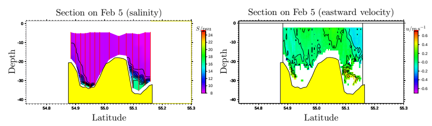

Figure 6 Observed salinity and eastward velocity on a north-south transect across Kriegers Flak. (Feb 5, CTD and ADCP measurements)

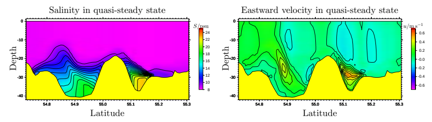

Figure 7: Simulated salinity and current velocity in quasi-steady state on a north-south transect at 13°E across Kriegers Flak. (GETM model)

The model result basically reproduces these observations of salinity and current velocity north of Kriegers Flak, see figure 7. Salinities north of Kriegers Flak reach up to 21 psu. As in the observations, the halocline is sloping towards Kriegers Flak in the northern channel. In further agreement with the observations, maximum eastward current velocities of up to 0.5 ms^{-1} are observed in the halocline. On Feb 7, during a 24 h station north of Kriegers Flak (see figure 1), velocity and salinity profiles were observed by means of a ship-mounted ADCP and a free-falling micro-structure profiler. The results show that the 10 m thick bottom plume is still present. Salinities reach up to 20 psu flowing eastwards with current velocities up to 0.6 ms^{-1}, see figure 8. The plume is overlaid by brackish water with salinities of 8-9 psu with a sharp interface between plume and ambient water.

Also here, the idealised simulation reproduces most of the observed features quite well, see figure 8. A predominant feature of the velocity structure is the sharp eastward velocity peak visible in the observations as well as in the model results. This peak is associated with the lower limit of the halocline. It can be explained by the fact that at this position the internal pressure gradient still has its maximum value while the bed friction decreases due to the stratification in the halocline.

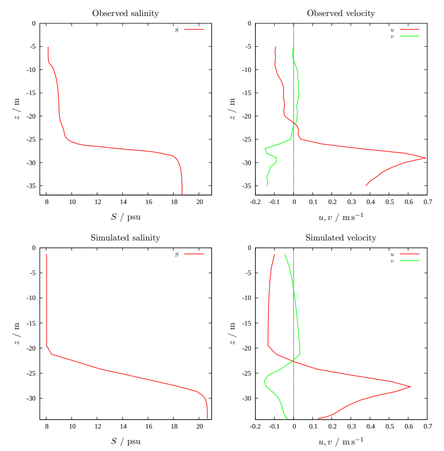

Figure 8: Observed salinity and current velocity (upper panels) and simulated salinity and current velocity (lower panels) at a position north of Kriegers Flak during a medium-intensity inflow situation on Feb 7 at 4 am. Shown for the observations are hourly averages. The observational data have been obtained by FWG Kiel, Germany, the model simulations have been carried out with GETM.

4 Conclusions

This combined observational and model study reveals that the typical pathway of mediumintensity saline plumes over Drogden Sill passes Kriegers Flak northwards. The observed general structure of the plume is in good agreement with the idealised model simulation. Main features are strong shear and stratification at the interface between plume and ambient water, with a velocity jump of more than 0.5 ms^{-1} and a salinity jump of more than 10 psu over 3 m.

The understanding of these events in the Arkona Sea is of interest, since extensive offshore wind farms are planned in this area. An accumulation of such constructions in the pathway of dense bottom water could lead to a dilution of dense bottom water and decreased ventilation of the halocline in basins further east such as the Bornholm Sea. For the large bridge projects across the Great Belt and the Sound, the so-called zero blocking solution had been proposed, see Hansen and Møller [1989] and Stigebrandt [1992], meaning that no changes of the transport of water and salt between the Baltic Sea and the North Sea should occur. Concerning offshore wind farms such internationally coordinated environmental impact strategy has not yet been developed.

Acknowledgements:

The work for this study was carried out in the framework of the international QuantAS Consortium (Quantification of water mass transformation processes in the Arkona Sea), which is partially funded by the QuantAS-Off project (QuantAS - Impact of Off-shore Wind Farms) by the German Federal Ministry of Environment, Nature Conservation and Nuclear Safety (BMU).

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